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MILLIMETER WAVE HOLOGRAPHICAL INSPECTION OF HONEYCOMB COMPOSITES (PREPRINT)

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14. ABSTRACT
Multi-layered composite structures manufactured with honeycomb, foam, or balsa wood cores are finding increasing utility in a variety of aerospace, transportation, and infrastructure applications. Due to the low conductivity and inhomogeneity associated with these composites, standard nondestructive testing (NDT) methods are not always capable of inspecting their interior for various defects caused during the manufacturing process or as a result of in-service loading. On the contrary, microwave and millimeter wave NDT methods are well-suited for inspecting these structures since signals at these frequencies readily penetrate through these structures and reflect from different interior boundaries revealing the presence of a wide range of defects such as disbond, delamination, moisture and oil intrusion, impact damage, etc. Millimeter wave frequency spectrum spans 30 GHz - 300 GHz with corresponding wavelengths of 10 - 1 mm. Due to the inherent short wavelengths at these frequencies, one can produce high spatial resolution images of these composites either using real-antenna focused or synthetic-aperture focused methods. *See reverse for conclusion*

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MILLIMETER WAVE HOLOGRAPHICAL INSPECTION OF HONEYCOMB COMPOSITES

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Keywords: Honeycomb Composites, Millimeter Waves, Holography
PACS: 81.70.Ex, 84.40.-x, 77.84.Lf, 07.60Hv, 68.37.Uv

INTRODUCTION

Microwave and millimeter wave nondestructive testing (NDT) techniques have been effectively used for inspection of a wide variety of complex composite structures. These investigations have primarily used near-field [1-9] or focusing lens [9-10] techniques for testing, evaluation, material characterization and imaging. The ability of

these signals to readily penetrate inside of composite structures, their relatively short wavelengths and the fact that near-field and focusing lens inspection produces high spatial-resolution images makes these techniques extremely attractive, viable and in some cases unique for the purpose of composite inspection. There are other advantageous attributes that these techniques possess and the entire list along with pertinent discussions can be found in [1,9].

There are two significant attributes associated with these signals that make them very attractive for producing synthetic-aperture and holographical images; namely, the relatively wide bandwidth associated with various millimeter wave bands and the ability to perform coherent measurements (e.g., availability to measured magnitude and phase referenced to a known plane). The latter provides for the necessary requirement of coherent signal addition when producing a synthetic-aperture image, which inherently possesses high spatial resolution [11-12]. The former provides for high depth resolution (similar to a narrow pulse in time domain) and hence allows for holographic algorithms to be used to produce a high-resolution three-dimensional (3D) image of an object or a composite structure [12-14]. In addition to producing a high-resolution 3D image, one can also slice the 3D image at various depths (depending on the available signal bandwidth) and hence, create image slices similar to those produced by X-ray computed tomography. Microwave holography, as described above has recently been successfully used for acreage heat tile and spray-on-foam-insulation (SOFI) imaging of the Space Shuttle structural components [14].

To describe the method simply, a compensation of the round trip phase is performed for wave signals originating from points on a plane to an arbitrary located target using angular spectrum decomposition. This requires a swept-frequency measurement of the complex microwave reflection coefficient over a plane, which for the purpose of this investigation, was taken using an open-ended waveguide probe over the Q-band (33-50 GHz) frequency range. The resulting dataset is a volumetric representation of the specimen and can be graphically illustrated as such. The spatial resolution is approximately one quarter of the mid-frequency wavelength and the range resolution is $c/2B$, where c is the speed of light and B is the transmitted signal bandwidth, which in this case is 17 GHz [12-13]. For a signal originating at a point target, signals add constructively, otherwise the signals add destructively, resulting in a high-resolution image. For processing purposes, it is assumed that the wave is not delayed as it propagates through air or the honeycomb composite sample. This assumption is acceptable since the interior of the composites is made of honeycomb with a dielectric constant close to that of free-space. Therefore, image processing is used to aid in finding reflections occurring at air to honeycomb interfaces.

DESCRIPTION OF PANELS AND PREVIOUS RESULTS

Two honeycomb composites panels (1”-thick and 0.5”-thick) were evaluated. Each panel had one side bonded with a thin glass fiber reinforced polymer (GFRP) laminar skin and the other side bonded with a thin multi-directional carbon fiber reinforced polymer (CFRP) skin. The panels appear to be produced with several embedded defects made out of thin polymer sheets (i.e., Teflon tape, plastic, paper, etc.) and missing honeycomb/skin material. The embedded defects primarily represented planar disbonds, crushed core, and delaminations at various heights within the thickness of the panels and with different shapes. The first panel (Panel #1) was a 1"-thick honeycomb sample produced by stacking two 0.5”-thick honeycomb layers on top of one another with a mid-thickness composite septum separating the honeycomb layers. The second panel composite (Panel #2) similarly

was manufactured except that it had a single layer of 0.5"-thick honeycomb core [15].

These panels were used in an earlier investigation for the purpose of comparing the ability of several NDT methods, including near-field millimeter waves, X-ray computed tomography (CT), shearography and through-transmission ultrasound, for inspecting these panels. The results indicated that X-ray CT and near-field millimeter wave NDT methods scored very high in terms of detecting the most number of inserts while providing high spatial resolution images, as shown in Table 1. In addition, the X-ray CT provided very high depth resolution as well as image slices of the samples [15]. Thus, in the investigation we will focus on comparing the millimeter wave holographical results with those from the X-ray CT.

Table 1. Summary of detection and resolution attributes of the four NDT methods [15].

	Detection (Number of Flaws)		
	Panel #1	**Panel #2**	**Lateral Resolution**
X-Ray CT	8	7	High
Near-Field Millimeter Wave	6	7	High
Shearography	4	6	Low
Through-Transmission UT	4	5	Moderate

RESULTS

Figures 1 and 2 show several X-ray CT slices of the two panels obtained from the previous investigation [15]. These results clearly show the relative size and location of the various embedded flaws in these samples. Figure 3a shows the picture of the measurements setup with the Q-band open-ended waveguide probe held approximately 22 mm above Panel #1. Since the bottom skin of this and Panel #2 is made of multi-directional CFRP sheet, millimeter waves reaching the bottom skin are reflected back towards the probe (i.e., this sheet acts as a very good reflector of millimeter wave signals).

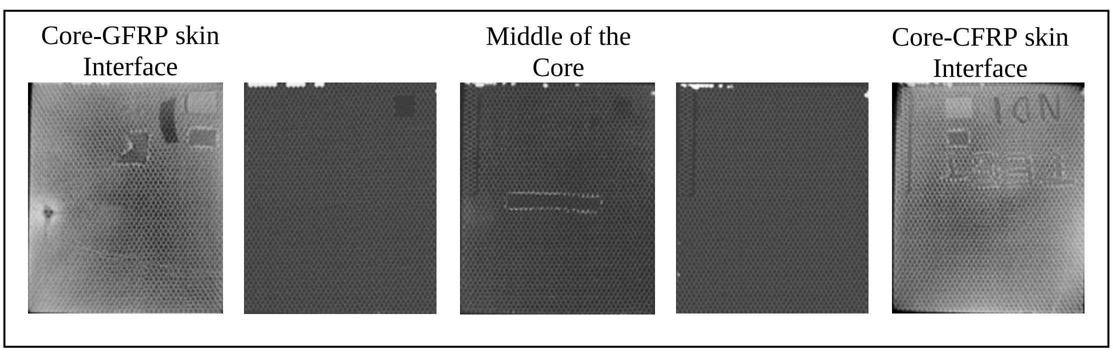


Figure 1: X-ray CT image slices of panel #1.

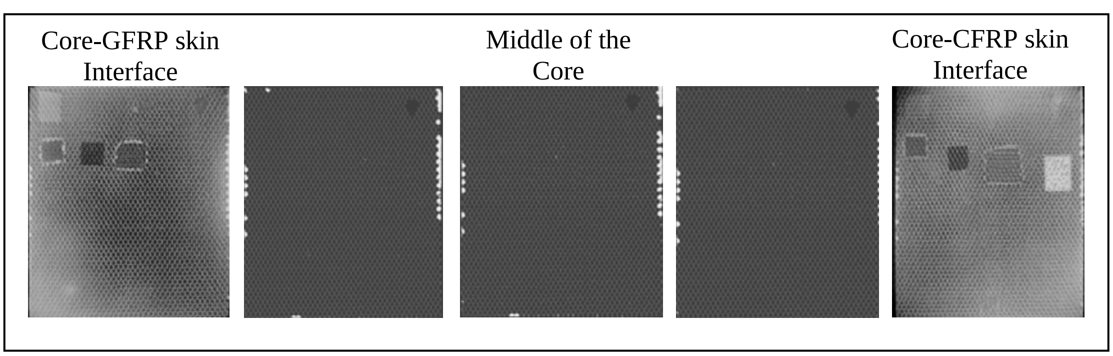
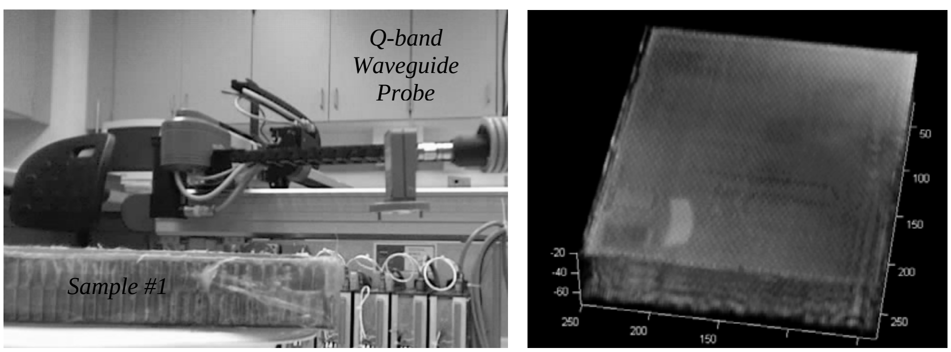


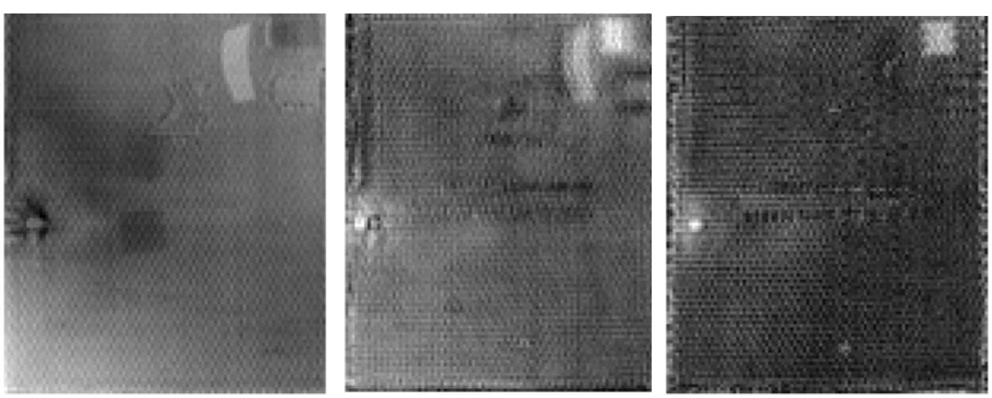
Figure 2: X-ray CT image slices of panel # 2.

Figure 3b shows a 3D-view of Panel #1 showing several of the flaws under the top skin. This 3D image (hologram) is an impressive demonstration of the utility of millimeter wave holography for thick composite inspection. Figures 4a-c show three different slices of the hologram at three different depths within Panel #1; namely, the region immediately corresponding to the top of the panel, 8 mm below the top surface, then 6 mm below that, respectively. There are several important observations that must be made with respect to the results shown in Figure 4. The spatial resolution associated with this holography technique is approximately half of the dimension of the waveguide probe aperture (in each direction). Given that at Q-band the aperture dimension of the waveguide probe is 5.7 mm by 2.8 mm, one can see the high spatial resolution associated with images in Figures 3b and 4a-c. The spatial resolution associated with these images provides similar image interpretation capability as those images obtained using X-ray CT. The transmitted signal bandwidth for these measurements was 17 GHz. Therefore and as explained earlier, the depth resolution associated with these images is ~8.8 mm. This is clearly not as fine of a resolution as that obtained by the X-ray CT. Therefore, when considering the hologram slice images in Figure 4, flaws under the skin (Figure 4a) also appear in Figure 4b. However, it is important to note that at each depth the flaw associated with that depth looks much more focused and clear compared to the same flaw observed in slices as when looking at a slice less than a resolution depth away. Collectively, these results show the tremendous capability and utility of millimeter wave holography for comprehensive 3D inspection of thick composite structures.



(a) (b)

Figure 3: a) Measurement setup and b) 3D view (hologram) of Panel #1.



(a) (b) (c)

Figure 4: Hologram slices of Panel #1 at relative distances from the probe of a) 24 mm, b) 32 mm and c) 38 mm.

Figure 5 shows the picture of the measurement set up for Panel #2. This panel was thinner than Panel #1. Therefore, the preceding discussions with respect to depth resolution apply even more to this panel. Figure 6a-c show three slices of the hologram of this panel, clearly showing the embedded flaws and the associated spatial resolution. The results show that even for this thinner panel, millimeter wave holography is a very useful imaging technique for evaluating interior characteristics of the panel.

SUMMARY

Millimeter wave holography is an effective and useful imaging techniques for evaluating interior characteristics of thick composite panels with honeycomb, balsa wood or foam cores. The large signal bandwidth associated with millimeter wave signals, the relatively small waveguide probe dimensions at these frequencies, along with available synthetic and holographical algorithms provides a great opportunity for an exciting area of imaging and nondestructive testing of composite structures. The results of two panels shown in this paper indicate that at Q-band (33-50 GHz) the spatial resolution associated with the images is excellent (in the few mm range) for nondestructive testing purposes. In addition, the depth resolution associated with the images also provides ample information with respect to the depth at which an embedded flaw may exist. The results also provided similar information to those obtained by X-ray CT. However, there are several advantageous practical features associated with millimeter wave holographical imaging techniques, such as safety, portability, relatively low cost, weight, and size that make them very attractive for practical nondestructive testing purposes.

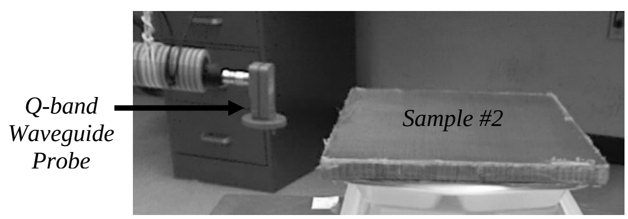
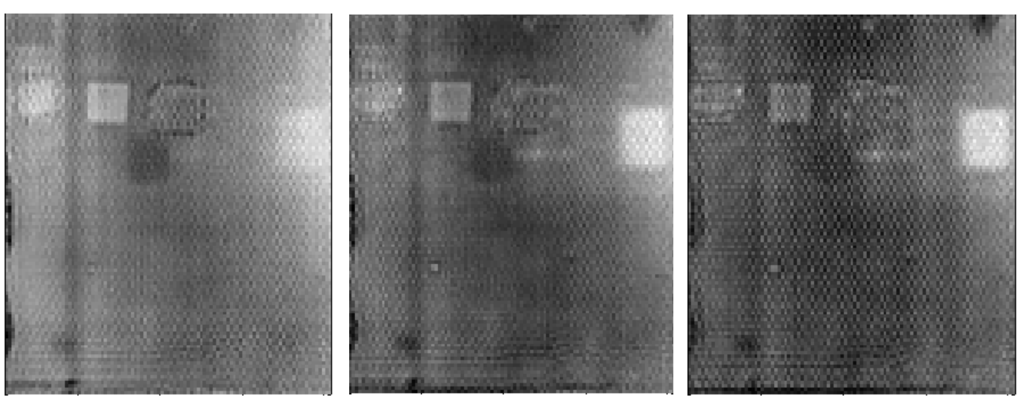


Figure 5: Measurement picture for Panel #2.



(a) (b) (c)

Figure 6: Hologram slices of Panel #2 at relative distances to the probe of a) 36 mm, b) 38 mm and c) 40 mm.

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